Chapter 2
Link and System Design

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Laser communications (lasercom) technology offers the potential for significantly increasing in data return capability from deep space to Earth. Compared to the current state of the art radio frequency (RF) communications links, lasercom links operate at much higher carrier frequencies (approximately 200–300 terahertz [THz]) compared to 32 gigahertz (GHz) for state of the art Ka-band deep-space RF links). The use of higher carrier frequencies implies a much smaller diffraction loss (e.g., much narrower beamwidth), which in turn, results in a much higher efficiency in delivering the signal energy. This improved energy delivery efficiency allows an optical link to operate at a lower transmit power and aperture size while still achieving a higher link data rate. Furthermore, unlike RF links where the spectral allocation and available channel bandwidth are tightly regulated due to interference concerns, the optical link is highly directional and virtually free of spectral constraints.

Although the lasercom system offers the potential for a small aperture high-data-rate transmission system, implementation of the lasercom system demands design considerations not commonly required for RF communications systems. This is principally because of the narrow transmission beamwidth of the optical signal. In order to efficiently deliver the signal and to reduce to probability of pointing-induced signal fades, the transmitter pointing error typically needs to be maintained within a small fraction of the transmit beamwidth. For a typical size aperture being considered for near-Earth and deep-space lasercom missions, the transmit beamwidth is typically on the order of a few microradians, and the required pointing accuracy is a small fraction of a microradian. The flight lasercom terminal must achieve this pointing accuracy in the presence of spacecraft platform jitter and attitude control deadband, both of which can be several orders of magnitude larger than the required pointing accuracy.

Over the last two decades, a number of lasercom flight demonstrations have been flown to demonstrate the technical feasibility of using modulated laser signals for high-rate data transport over free space. These flight experiments, mostly conducted with aircraft and spacecraft in the Earth vicinity, have demonstrated the technical feasibility of establishing and maintaining two-way precision beam pointing between transmit and receive terminals, and the capability of maintaining high-rate data links through the free-space optical channel. These flight experiments also led to the development of high-power space-qualified laser transmitters, optics, and precision beam-pointing hardware, as well as the resulting increase of NASA interest for further exploring the feasibility of using laser communications for deep-space missions.[1]

Even though these previous flight experiments established the feasibility of lasercom systems for near-Earth applications, deep-space missions can impose significant challenges such that a straightforward scaling of the near-Earth lasercom system architecture to deep-space distances would lead to unacceptable link performance. These differences come primarily from the longer link distance involved. The distance covered by the Mars mission ranges from two thousand times (Mars at closest approach) to ten thousand times (Mars at solar conjunction) the distance from Earth to geosynchronous Earth orbit (GEO). The longer link distance translates into larger aperture, higher power, and greater receiver sensitivity requirements for the deep-space link. Pointing and tracking a narrow signal from deep-space distances are also significantly more difficult due to the large link distance and long round-trip light time (RTLT). Additionally, deep-space missions need to handle a wide range of operating conditions and trajectory constraints. For example, solar conjunction outages for GEO satellites typically last for tens of minutes, whereas for planetary missions the solar conjunction outage can last from several days to several weeks, depending on how closely the optical system can operate to the Sun near its optical boresight. Because of the higher launch costs

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[1] The need for deep-space optical communications has been articulated in the NASA 2003 Strategic Plan [1] as a "New Effort Building Block" under the "Communications Technological Barrier" for "providing efficient data transfer across the solar system." The Strategic Plan identifies optical communications as necessary to "vastly improve communication to transform science capability, with a first demonstration from Mars." NASA's Science Mission Directorate expressed the need for optical communications as "the Optical Communications Initiative will demonstrate critical space and ground technologies in this decade and perform a flight demonstration of high-data-rate communication from Mars in the 2010 timeframe."

and longer mission lifetimes, deep-space missions generally place a premium on mass and power of the flight terminal, and have a more stringent mission reliability requirement. Finally, unlike RF system designs, where a well-defined ground network can be used to help define the flight terminal requirement, no such infrastructure exists for the deep-space optical network. As a result, system designers will need to evaluate design drivers for both the deep-space equipment and the Earth terminals in order to arrive at the proper design.

Given the relative complex set of trades required to define the deep-space lasercom system, the purpose of this chapter is to provide an overview of the major design drivers for a deep-space lasercom system and their implications for flight terminal and ground network design and implementations, and to provide a context for more in-depth discussion in subsequent chapters. These drivers include:

1) Communications link performance,
2) Beam Pointing and Spatial Acquisition,
3) Laser safety,
4) Other considerations such as mass, power, and impact on spacecraft.

2.1 Overview of Deep-Space Lasercom Link

An overview of a generic deep-space lasercom link is shown in Fig. 2-1. The link consists of a lasercom flight terminal aboard the deep-space spacecraft, an optical channel, and one or more Earth terminals. The flight lasercom terminal interfaces with the host spacecraft, which provides power, control, ephemeris and pointing information, and coarse attitude control. The flight lasercom terminal also receives the downlink data stream from the spacecraft and delivers the uplink data to the spacecraft. The functions of the flight lasercom terminal are to:

1) Encode and modulate the downlink information onto an optical carrier,

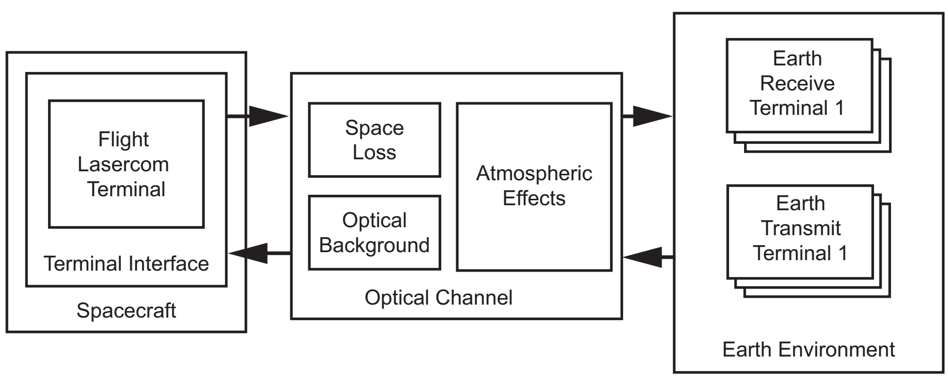

Fig. 2-1. Overview of a deep space lasercom link.

2) Provide an appropriate optical power and transmit antenna gain in order to close the communications link,
3) Acquire the appropriate pointing reference and point the downlink signal at the Earth terminal,
4) Provide suitable pointing stabilization functions against the platform jitter and spacecraft attitude control deadband, and
5) Provide appropriate receiving antenna gain and detection sensitivity to receive uplink data from the Earth terminal.

The signal passes through an optical channel, which adds space loss ($1/Z^2$ loss) to the signal. The optical channel also introduces background noise at the receiving terminal. The major sources of the background noise are the Sun, the Moon, the planets, and bright stars. If the Earth terminal is ground based, the signal also passes through the atmosphere, which introduces additional background (sky irradiance), attenuation, and signal scintillation. In addition to clear weather attenuation, an optical signal passing through the atmosphere can also be severely attenuated by clouds. Effective communications through clouds is not a feasible solution as cloud attenuation can be upwards of tens of dB in some cases (e.g., cumulus nimbus), and appropriate operational workaround needs to be considered as part of the optical link design. Atmospheric scintillation is also an important effect because it breaks up the spatial coherence of the optical signal. As we shall see, this effectively prevents the use of coherent optical reception technique for a ground-based receiver. For an optical uplink, atmospheric scintillation can lead to beam wander and fades at the receiving end, which must be considered when designing an optical uplink.

The optical downlink from the flight lasercom terminal is received by one or more Earth receive terminals. The functions of the Earth receiving terminals are to provide

1) Appropriate receiving antenna gain and sensitivity to receive, demodulate, and decode the optical downlink.
2) Suitable pointing accuracy of the receiving antenna in order to direct the downlink onto the receiving detector while limiting the amount of background signal admitted by the receiving optics.
3) Sufficient spatial diversity to support the mission/link availability requirements.

In addition to the receiving terminals, one or more Earth transmit terminals may also be deployed if either optical uplink communications is required, or the flight terminal pointing acquisition and tracking scheme requires the use of an Earth-based reference beacon to direct the downlink signal. The functions of the Earth transmit terminals are to provide

1) Sufficient optical power, pointing accuracy, and directivity in order to deliver the required uplink signal flux at the flight lasercom terminal for uplink communications or for beacon pointing.
2) Sufficient spatial diversity to support the mission/link availability requirements.

The Earth terminal(s) can be either ground based or balloon/aircraft/spacecraft based. The latter can communicate above much or all of the Earth atmosphere, thus having significant operational advantages. However, because of the large aperture required to support the deep-space link, the lifecycle costs for a balloonborne, airborne, or spaceborne terminal are much higher, and the logistics of supporting a flight terminal are significantly more difficult than those of a ground-based terminal. Consequently, most of the studies performed to date have assumed a ground-based Earth terminal. However, as technologies for lightweight optics continue to develop, such terminals may eventually present feasible options. For the remainder of this Chapter, we shall assume that the Earth terminal is ground based. In order to provide a suitable amount of link availability, it is envisioned that a network of ground stations will be required.

2.2 Communications Link Design

The capability to support (and achieve) a very high downlink data rate is the principal benefit for the deep-space lasercom technology. Given the existing capability of the Deep Space Network (DSN) and the relative maturity of RF communications technology at X-band (8 GHz) and Ka (32 GHz) band, the deep-space lasercom technology needs to achieve a significant data-rate advantage over the existing RF implementation before it can be seriously considered for future missions.

A useful metric for comparing the end-to-end communications link performance is the data rate-distance square product. The current state-of-the-art near-Earth lasercom system supports upwards of a 10 gigabits per second (Gbps) link from GEO distance. Using the data rate-distance square product metric, such a system will scale to approximately 100 bits per second (bps) at Mars distance and 0.25 bps at Pluto, as shown in Fig. 2-2; which is grossly inadequate for the deep-space mission requirements.

In contrast, the performance of several currently on-going or near-term deep-space RF communication systems is shown in Table 2-1 and plotted against the state-of-the art optical link performance in Fig. 2-3. It is seen that both the Cassini and the 2005 Mars Reconnaissance Orbiter (MRO) achieved major link performance advantages over the current state-of-the art optical link (i.e., Geolite). In order to be competitive against the RF system performance, significant improvements (>50 dB) in optical link performance are required.

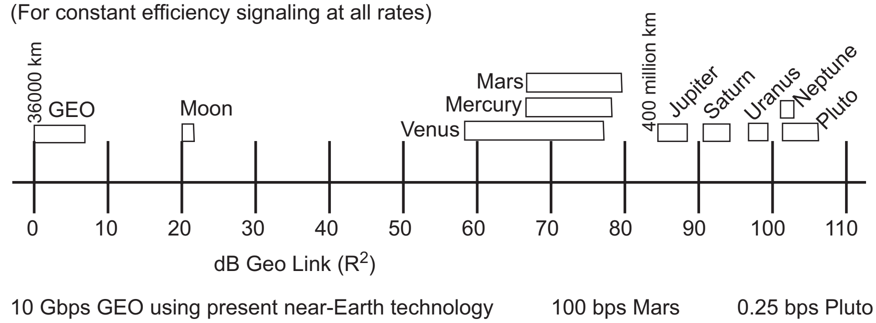

Fig. 2-2. Scaling of lasercom link performance over distance.

Table 2-1. Current RF link performance.

Mission	Communications System	Performance
Cassini	20-W X-band TWT, 4-m HGA	14 kbps at 10 AU
Mars Odyssey	15-W X-band SSPA, 1.3-m HGA	4–110 kbps at 2.6 AU
Mars Reconnaissance Orbiter	100-W X-band TWT, 3-m HGA	500 kbps at 2.6 AU
	35-W Ka-band TWT	300 kbps at 2.6 AU

(AU = astronomical unit [1.496 x 10^{11} m], HGA = high-gain antenna, SSPA = solid state power amplifier, TWT = traveling wave tube)

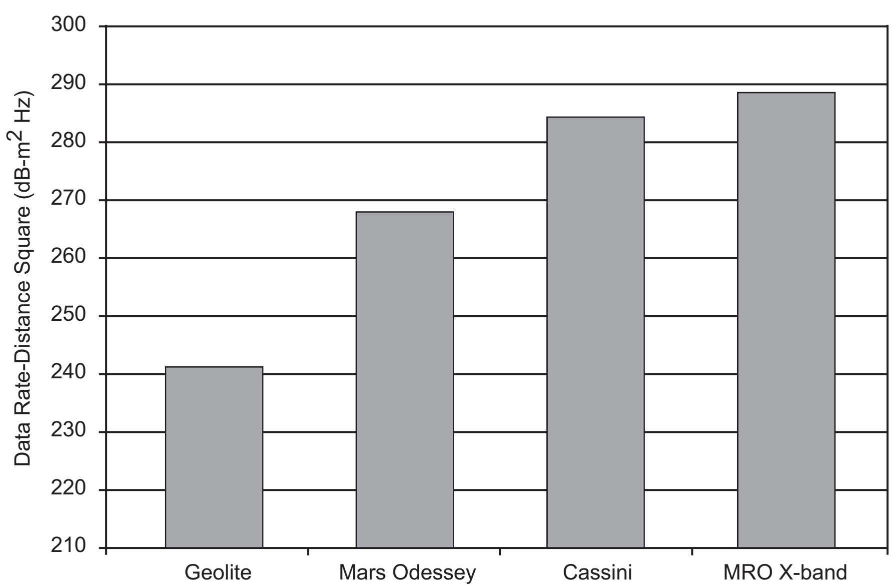

Fig. 2-3. Figures of merit comparison between a current lasercom system and selected RF systems.

Achieving the large performance improvement over current state of the art will require attentions in the following areas:

1) Improving the amount of signal power delivered to the receiver. This will include increasing the amount of transmit power and antenna gains, as well as the efficiency of the optics and pointing performance.
2) Improving the receiver sensitivity, measured in terms of effective delivered bits per received signal photon.

2.2.1 Link Equation and Receive Signal Power

The ability for an optical link to deliver the signal power to the receiver is governed by the link equation, which can generally be written as

$$P_S = P_T\left(\eta_T\eta_A\frac{4\pi A_T}{\lambda_T^2}\right)L_{TP}L_{atm}L_{pol}L_{RP}\left(\frac{A_R}{4\pi z^2}\right)\eta_R \qquad (2.2\ 1)$$

where

- P_S is the total signal power at the input to the receiver. For the uplink, this is defined at the input to the optical detector. For the downlink, the receive signal power is defined at the input to the receive optical detector.
- P_T is the transmit optical power at the transmit antenna interface.
- η_T is the transmit optics efficiency.
- η_A is the aperture illumination efficiency of the transmit antennas.
- λ_T is the transmit wavelength.
- A_T is the aperture areas, respectively.
- L_{TP} is the transmitter pointing loss, defined as the ratio of power radiated in the direction of receiver to the peak radiated power. If the transmitter is directly pointed at the receiver, the pointing loss is 0 dB.
- L_{atm} is the fractional loss due to absorption of the transmitting medium (e.g., Earth atmosphere and any occluded planet atmospheres)
- L_{pol} is the fractional signal loss due to mismatch of the transmit and receive antenna polarization patterns.
- A_R is the receive aperture area.
- z is the link distance, and the term $\left(A_R / 4\pi z^2\right)$ is the fraction of power that is collected by the receiving aperture if the transmitter is an isotropic radiator.

L_{RP} is the receiver pointing loss, defined as the ratio of receive antenna gain in the direction of the transmitter to the peak receive antenna gain.

η_R is the receiving optics collecting efficiency, defined as the fraction of optical power at the receiving aperture that is collected within the field of view of the receive detector.

Improving the receive signal power, therefore, can be accomplished by the following means:

1) Increasing the transmit power. The most straightforward method of improving the receive signal power is to increase the power at the transmitter since the receive power scales linearly with the transmit power. However, increasing the transmit power also increases the overall system power consumption which, for a deep-space mission, is typically at a premium. Furthermore, the increased power consumption can lead to thermal management issues (increased radiator size and hence mass) for the host spacecraft, as well as reliability concerns.
2) Increasing the transmit aperture. This effectively reduces the transmit beamwidth and hence improves the power delivery efficiency. However, the pointing and tracking of the narrow downlink becomes increasingly more difficult with a narrower downlink. Furthermore, the aperture size is highly correlated with the mass of the transmit terminal and hence cannot be increased indefinitely.
3) Reducing the operating wavelength. Reducing the operating wavelength reduces the diffraction loss of the signal (i.e., reduces the transmit beamwidth). However, the wavelength selection is strongly constrained by the available laser technology, as well as considerations on the receiver sensitivity and detector technology. Furthermore, the transmittance of the atmosphere also depends on the wavelength, as well as the amount of sky background irradiance.
4) Increasing the receiver aperture area. Since the receive signal power scales linearly with the receive aperture area, increasing the receiver aperture area is a relatively simple way to improve the system performance. However, for daytime operations of a receiver inside the Earth's atmosphere, the amount of background noise collected also increases with increasing receiver aperture, and the effective performance improvement does not always scale linearly with increasing aperture area.
5) Reduced pointing loss. Reducing the pointing loss improves the overall signal energy and also reduces the point-induced signal power fluctuation.
6) Improving the overall efficiency, including transmit and receive optical loss, and polarization mismatch losses. This generally requires attention to the optical design. Of particular attention is the transmit optics design. The

transmit aperture illumination efficiency, η_A, depends on the phase and intensity distribution over the aperture. For the general case of a transmit aperture being illuminated by a Gaussian beam, the aperture illumination efficiency can be written as:

$$\eta_A = \frac{2S}{\alpha^2}\left[\exp\left(-\alpha^2\gamma^2\right) - \exp\left(-\alpha^2\right)\right]^2 \quad (2.2\text{-}2)$$

where α is the ratio between the aperture diameter and the Gaussian beam $\left(1/e^2\right)$ diameter of the transmit signal, and γ is the obscuration ratio. The term S in Eq. (2.2-3) is known as the Strehl ratio, which is defined as the intensity at the center of the aberrated system to that of an ideal optical system. The Strehl loss is given by

$$S = \exp\left(-(2\pi\sigma / \lambda)^2\right) \quad (2.2\text{-}3)$$

where σ is the root mean square (rms) optical path difference, which for smooth optics is approximately 28 percent of the peak-to-valley differences. For a $\lambda/16$ optical system, for example, the Strehl ratio is approximately 86 percent, or approximately a 0.65-dB loss.

2.2.2 Optical-Receiver Sensitivity

In addition to the effective delivery of the signal to the detector, the performance of the optical link also depends on the receiver sensitivity (measured in terms of received photons per bit). Because of the high cost associated with increasing the transmit power and system aperture, improving the receiver sensitivity is an important factor in the deep-space lasercom system design.

Either a coherent receiver or a direct-detection receiver can be used to detect the optical signal. In a coherent optical receiver, the incoming signal is mixed with the output of a strong local oscillator (LO) beam, and the interference between the signal and LO in the combined field is detected using a pair of photodetectors. Figure 2-4 shows a conceptual block diagram of a coherent receiver.

The mixing of the weak signal field and the strong LO field at the front-end of a coherent receiver provides linear amplification and down-converts the optical signal into an electrical output at the intermediate frequency (IF) with gain (usually tens of decibels). With a sufficiently strong LO field, this raises the signal level well above the noise level of subsequent electronics. The sensitivity of the coherent receiver is thus limited by the self noise (i.e., signal shot noise) of the incident signal. Furthermore, because of the spatial mixing process, the coherent receiver is sensitive only to

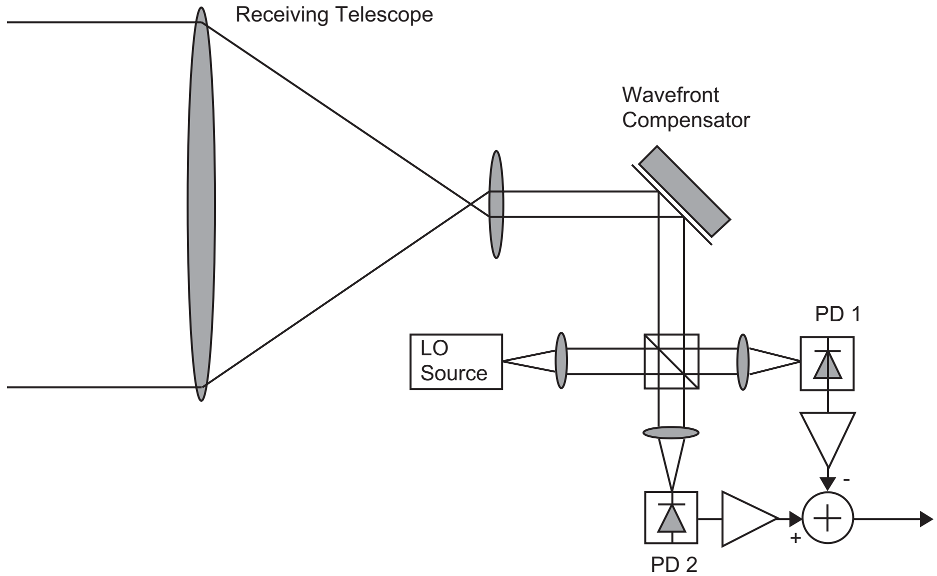

Fig. 2-4. Coherent optical receiver conceptual block diagram.

signal and background noise that falls within the same spatial-temporal mode of the LO. A coherent receiver can, in principle, operate with a very strong background (e.g., with the Sun in the field of view) without significant performance degradation.

The capacity of the coherent optical channel can be written as

$$C_{Coherent} = \left(\log_2 e\right) B \ln\left(1 + \frac{\lambda_S}{B}\right) \approx \left(\log_2 e\right) \lambda_S \qquad (2.2\text{-}4)$$

where λ_S is the rate of detected signal photons, and the last approximation was made in the limit of large signal bandwidth B. Equation (2.2-4) states that the limiting capacity of a heterodyne optical channel is ~1.44 bits per detected photon.

Even though the coherent receiver can in principal provide near-quantum-limited receiver sensitivity, such performance is achieved only through near-perfect spatial-mode matching between the incoming signal and the LO. The added complexity to accomplish the spatial wavefront matching can be very difficult to achieve for a ground-based receiver. This is because the atmosphere effectively breaks up the incident wavefront into a number of coherent cells of sizes approximately the coherence length of the atmosphere r_0. The size of r_0, under typical operating condition, is on the order of 5–30 cm. Although adaptive optics techniques have been developed to partially compensate for the wavefront distortion, effective wavefront correction over the large aperture diameter envisioned for the deep-space receiver will require an active mirror with a large number of actuators. Because of the complexity of such a system, and because the simpler direct-detection receivers have managed to achieve similar, if not better performance, coherent receivers are not being considered for a ground-based receiver. Instead, the bulk of the development has been focused on the direct-detection receiver.

In a direct-detection receiver, the received optical intensity is detected without extensive front-end optical processing. Figure 2-5 shows a conceptual block diagram of a direct-detection receiver. The incident signal is collected by the receive telescope. A polarization filter followed by a narrowband filter, and a field stop effectively reduces the amount of background noise incident onto the detector.

The capacity of a direct-detection optical link has been studied extensively. When the receiver is capable of detecting individual photons, Pierce [2] first showed that the capacity of the optical channel can be improved by using a modulation format with very high-bandwidth expansion ratios. Subsequent work by Wyner [3] showed that the capacity of a direct detention optical channel in the presence of background can be written as:

$$C = \left(\log_2 e\right)\frac{\lambda_S}{M}\left[\left(1+\frac{1}{\rho}\right)\ln\left(1+\rho\right)-\left(1+\frac{M}{\rho}\right)\ln\left(1+\frac{\rho}{M}\right)\right] \qquad (2.2\text{-}5)$$

where λ_S is the rate of arrival for the detected signal photon (measured in photons/sec), $\rho = \lambda_S / \lambda_B$ is the (detected) peak signal to background power

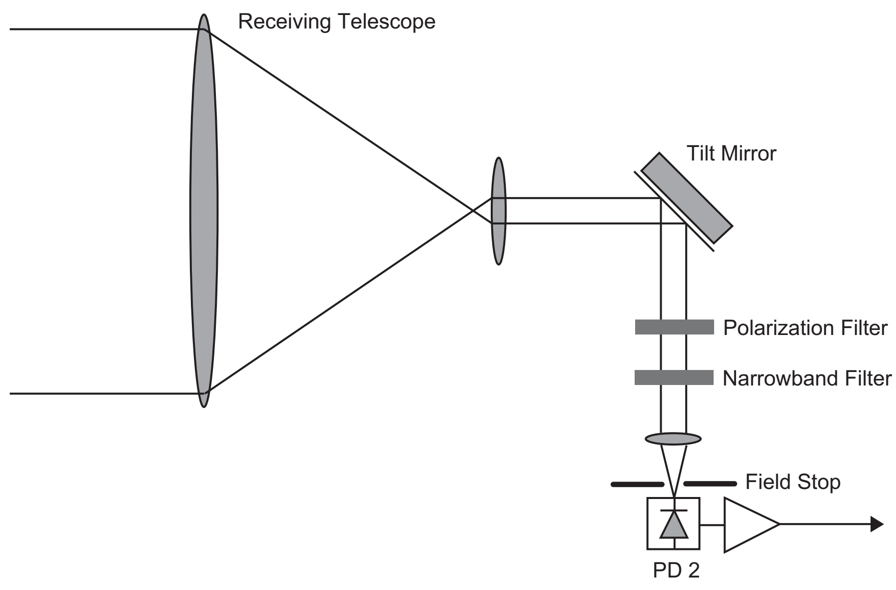

Fig. 2-5. Direct-detection optical receiver conceptual block diagram.

ratio and M is the peak-to-average power ratio of the signal. Figure 2-6 shows a plot of the channel capacity versus the peak-to-average signal ratio for several values of the average signal-to-background noise ratios. It is possible to transmit more than 1 bit/photon at a sufficiently high peak-to-average power ratio [12,13]. In other words, a photon-counting direct-detection receiver can achieve a higher channel capacity than a coherent receiver by using modulation formats that exhibit high peak-to-average power ratios.

Eq. (2.2-5) shows that the capacity of a direct detection optical link using ideal photon-counting detector can be improved by

1) Improving λ_S, or equivalently, increasing the photon detection efficiency for a given receive optical power level,
2) Increasing M, the peak to average power ratio: the performance of the direct detection optical channel can be improved by selecting a modulation format that maintains a high peak to average power ratio,
3) Improving ρ, the signal to noise power ratio by limiting the amount of background optical power detected by the photodetector.

Even though Eq. (2.2-5) was derived from an ideal photon-counting receiver model, the general behavior of the channel capacity remains valid for a wide range of receivers/detectors that are shot-noise limited. That is, the performance of the direct-detection link can be improved by increasing the detector sensitivity, selecting a modulation format with high peak to average power ratio, and reducing the amount of background light detected. Each of these factors is briefly described below.

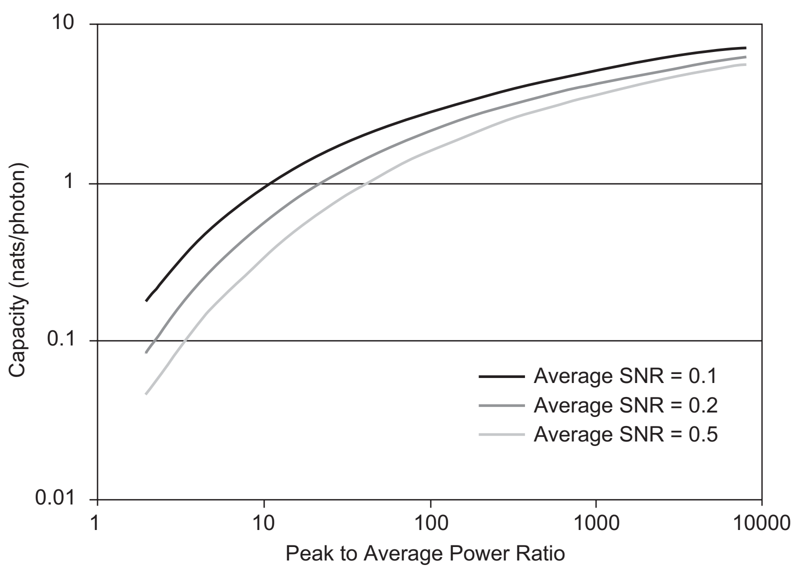

Fig. 2-6. Channel capacity versus peak-to-average power ratio for different signal/background noise ratios.

2.2.2.1 Photon Detection Sensitivity. Improving the photon detection efficiency is an obvious method of improving the channel performance. For a direct-detection receiver, this is generally accomplished by using detectors with internal amplifications, such as avalanche photodiodes (APDs) and photomultiplier tubes (PMTs).

In the limit of a very high amplification gain, the receiver's noise contribution can be ignored, and the receiver is capable of discriminating the individual photon arrival events and counting photons. If the detector contribute negligible amount of dark counts, such a receiver is capable of achieving the channel capacity shown in Eq. (2.2-5). For a more general class of optical receiver that is not capable of discriminating individual photon arrivals, the channel capacity will depend on the noise added by the receiver, including the noise introduced by the amplification process and the thermal noise from the circuit elements. Even if the receiver is not photon-counting, improving the receiver sensitivity can still result in a corresponding increase in the channel capacity. This is accomplished by increasing the detector amplification while controlling the noise introduced by the amplification process (e.g., excess noise) and the thermal/leakage current noise. Refer to Section 6.2 for more detailed discussion of the photon detection.

2.2.2.2 Modulation Format. One practical modulation format to achieve high peak-to-average-power ratio is the M-ary pulse-position modulation (PPM). In an M-ary PPM modulation scheme, each channel symbol period is divided into M time slots, and the information is conveyed through the channel by the time window in which the signal pulse is present. An illustration of the PPM modulation for a simple case of $M = 8$ is shown in Fig. 2-7.

When the transmit laser exhibits a sufficient modulation extinction ratio, the peak-to-average power ratio of an M-ary PPM channel is equal to M, and the capacity of the M-ary PPM channel closely approximates the ideal Poisson channel capacity stated in Eq. (2.2-7). Additionally, when $M = 2^k$, each PPM channel symbol can be mapped directly to a k-bits sequence, thus simplifying the bit-to-symbol mapping problem. For these reasons, except when the

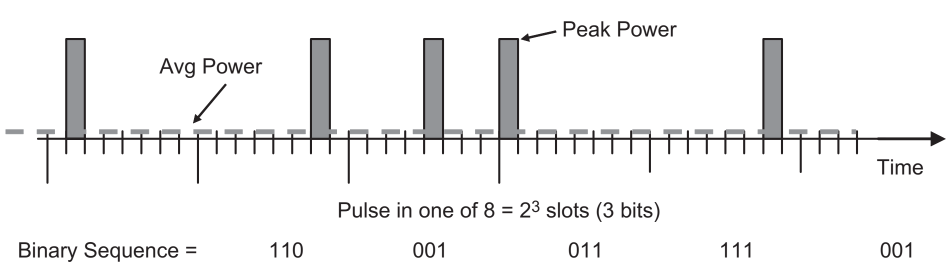

Fig. 2-7. Example of a M-ary PPM modulation with *M* = 8 and straight binary mapping.

transmitter is peak-power limited or when the system is modulation-bandwidth limited, most deep-space optical links analyzed to date had assumed M-ary PPM modulations. [4,5]

2.2.2.3 Background Noise Control. The discussion following Eq. (2.2-5) shows that the performance of the direct detection channel can be improved by reducing the amount of background noise detected by the receiver. For a typical ground based receiver, the sources of background noise include:

1) Diffused (extended) background from the atmosphere, The background irradiance from the extended background can be written as

$$P_{diffuse} = L_{\lambda}(\theta) A_R \Omega \Delta\lambda \eta_R \tag{2.2-6}$$

where $L_{\lambda}(\theta)$ represents sky radiance, which is a function of wavelength and solar illumination geometry, A_R is the effective receiver area, Ω is the solid angle field of view in steradians, $\Delta\lambda$ is the optical bandpass, and η_R is the efficiency of the optical receiving system.

2) Planetary or stellar background objects within the receiver field of view. For a point source (e.g., a star) in the receiver field of view, the amount of background power collected by the receiver is written as

$$P_{point} = H(\lambda) A \Delta\lambda \eta_R \tag{2.2-7}$$

where $H(\lambda)$ is the spectral irradiance of the background source, with units of watts per meter squared. micron.

3) In addition to the point sources and extended background sources, another major source of background photons is the scattered light collected by the receive optics. A strong background source near the field of view of the receiver can lead to significant scattering into the receiver field of view. For an optical receiver design with optics under direct exposure to sunlight, the scattering contribution is one of the major background noise sources [6]. The amount of scattered sunlight collected by the receiver can be written as

$$P_{stray} = I_{\lambda} \Delta\lambda \Omega A \eta_R T(\lambda) BSDF(\theta) \tag{2.2-8}$$

where $T(\lambda)$ represents the atmospheric attenuation and I_{λ} represents the exo-atmospheric solar constant (0.074 W/cm^{2}µm) and $BSDF(\theta)$ is the bi-directional scatter distribution function as a function of incident angle. The *BSDF* values depend on the surface micro roughness and contamination levels and, in general, they exhibit a power-law dependence to the scattering angle, θ.

In addition to the sunlight scattered off the optical surface, scattered light contribution can also come from scattering off the optomechanical structure inside the optical system. In general, analysis of the scattered light off the mechanical surfaces requires the use of special analytical tools to model the critical surface scattering and the resulting background photon flux. Analysis of the scattered light (other than the optics scattering) is beyond the scope of the current analysis. However, if operation near a bright background source is required, one will need to carefully budget for the scattered background and verify the budget via a series of analytical models and hardware tests.

4) Lastly, the detector itself can contribute "dark currents" which are indistinguishable from the incident photon response. For a well designed system, the contribution of dark current to the overall link budget is generally small.

Background light control is accomplished with a combination of filter, baffle, stops, and masks. For extended background light and out of field stray lights, the amount of background light can be controlled using a field stop that limits the incident light to those from a small angular region around the true direction of the downlink. The diffraction limited field of view of a telescope is approximately $2.44\lambda/D$ which, for a 1 m-class telescope operating at 1 μm, is approximately 2.5 μrad. However, atmospheric turbulence breaks up the incident wavefront into coherent cells with diameters on the order of r_0, the value of which, under typical operating conditions, ranges from a few centimeters to tens of centimeters. The net effect of the turbulence is to redistribute the incident signal energy over an angular region the size of λ / r_0. This effect is shown in Fig. 2-8, which shows the increase in detector area (field of view) required to encompass the downlink energy.

Since $D >> r_0$, a field of view much larger than the diffraction limit is required in order to collect most of the signal energy. Adaptive optics technique can be used to partially mitigate the effect of turbulence at the price of a higher complexity [11]. For the size of aperture being considered for deep-space receivers (several meters), full adaptive optics compensation will require mirrors with upwards of 10^4 actuators.

Another method of controlling the background is to limit the receiver optical bandwidth. This is generally accomplished using a narrowband optical filter. Single optical filters with bandwidths as narrow as 0.05 nm are currently available, and even narrower bandwidth filters have been demonstrated. Finally, the amount of scattered background noise can be controlled by careful control of the surface roughness and cleanliness level on all surfaces that can be directly illuminated by the Sun or by limiting the amount of direct sunlight incident on the optical surfaces.

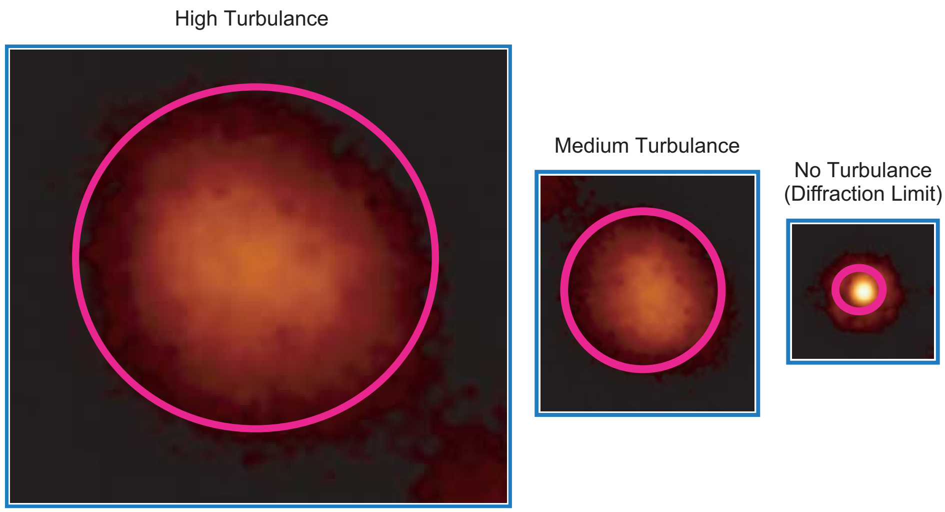

Fig. 2-8. Field-of-view increases induced by turbulence.

2.2.3 Link Design Trades

Design optimization for the optical link is generally accomplished by trading off various design considerations in iterative steps. Some examples of these high level trades include:

2.2.3.1 Operating Wavelength. The operating wavelength of the link is one of the major decisions. This decision is affected by considerations of the following:

1) Link Performance: In general, the antenna gain scales inversely with square of the operating wavelength, and it is more efficient to operate the link at a shorter wavelength. On the other hand, it is easier to maintain the optical quality and high Strehl ratio at longer wavelengths. Because the beamwidth scales inversely with wavelength, it is also easier to maintain pointing and reduce the pointing-induced signal fade at longer wavelength.
2) Availability laser technology and power: Considerations for the laser technology include peak-to-average power ratio, available peak power, electrical-to-optical conversion efficiency, and overall power consumption. Appropriate trades between the available laser technologies, which depend strongly on the operating wavelength, should be conducted to identify the proper design choice.
3) Attenuation and background noise power: The atmospheric loss does not explicitly depend on any link parameter. However, as the attenuation of the atmosphere depends on the absorption and scattering of the signal. The loss will depend on the wavelength choice. The amount of daytime background

noise is also a strong function of the operating wavelength, with a lower day-sky irradiance at a longer operating wavelength.

4) Detector sensitivity: the detector gain, detection efficiency, and excess noise factor determines the sensitivity of the detector in detecting incoming photons. Ideally, one would employ a detector with high-gain, large bandwidth, high efficiency, and low excess noise. However, the availability of such a detector is largely limited by operating wavelength. Silicon detectors, for example, can provide very high-gain bandwidth and low excess noise, but they have very little detection sensitivity at 1.5 μm.

2.2.3.2 Transmit Power and Size of Transmit and Receive Apertures. The power delivery efficiency of the link is proportional to the product of the transmit and receive aperture areas. Consequently, one can trade the size of transmit aperture on the spacecraft, which is typically mass and size constrained, with the size of ground receiver aperture. Furthermore, one can reduce the transmit power requirement by increasing the aperture size. For deep-space missions, the severe mass and power constraints generally lead to a highly asymmetric design. With the flight terminal's transmit power and aperture size limited by the available power and mass margin, a more viable option in improving the system performance is to increase the Earth receive aperture area. While a typical flight terminal has a transmit power of several watts and an aperture diameter of tens of centimeters, the equivalent aperture diameters for the Earth-receiving terminal under consideration generally ranges from a few meters to upwards of tens of meters. Note that since the performance depends on the total area, such an equivalent aperture can be made up from multiple smaller apertures.

The size of the aperture can also affect the pointing performance even though the pointing loss terms, L_{TP} and L_{RP}, do not explicitly depend on the link parameters. Since the beamwidth is inversely proportional to the aperture diameter, larger aperture optics will generally require a tighter pointing accuracy and higher sensitivity toward pointing loss. At the same time, a larger collecting aperture can lead to higher receive signal power and a lower noise equivalent angle.

2.2.3.3 Receiver Optical Bandwidth and Field of View versus Signal Throughput. The link performance can be improved by reducing the amount of optical background. This is accomplished by reducing the optical bandwidth and receiver field of view. Since the optical throughput can depend on the design of the narrowband filter and field of view, appropriate tradeoffs between the narrowband filter bandwidth, receiver field of view, and signal throughput are needed to optimize the link performance.

2.2.3.4 Modulation and Coding. Proper modulation and coding of the optical signal are required to achieve near-capacity performance. A modulation technique with a high peak to average power ratio is needed for the deep-space lasercom system, and optical PPM is generally regarded as an efficient modulation technique of choice. Other modulation techniques with an appropriate peak-to-average power ratio may also be implemented.

Once the modulation format is selected, appropriate channel coding should also be selected. A significant amount of work has gone into the development of channel coding for the optical channel. Earlier work has assumed the use of Reed Solomon (RS) codes that can be naturally mapped to the 2^k-ary alphabet of the PPM symbol. Recently, JPL has proposed the use of a serially concatenated PPM (SCPPM) code for deep-space optical links [9]. These codes can achieve near channel-capacity performance with a photon-counting detector, with a gap to capacity on the order of 0.75–1 dB. An in-depth discussion of the optical modulation and coding can be found in Chapter 4.

2.2.4 Communications Link Budget

As a tool for ensuring that pertinent system parameters related to link performance have been considered, a communications link budget is maintained through the design and built phase of the system development. The link budget is typically represented using a link design control table (DCT), which is a listing of design parameters and the resulting estimated system performance at a specific point in time during the mission. For RF systems, a rigorous and well-established link design procedure exists to calculate the end-to-end link performance and to document the link budget. System designers rely on such a DCT to conduct trade offs between transmit power, aperture size, and other system performance parameters. A similar procedure is used to conduct design tradeoffs for an optical link. Table 2-2 summarizes the typical design parameters that comprise a DCT. An example of a downlink budget from Mars is shown in [10].

2.2.5 Link Availability Considerations

The communications link budget or the DCT is a useful tool in estimating the physical layer link performance (e.g., the link bit error rate). An operational communications link, on the other hand, must also address the issue of link availability. Historically, deep-space RF communications links have achieved an overall link availability of approximately 90 percent. This number includes considerations of station downtime (from equipment failure) and weather-related outages. For RF links, weather-related effects contribute to only a small fraction of the link outages. In contrast, the optical link is much more susceptible to the channel effects, particularly when one end of the link resides within Earth's atmosphere. Additionally, operational constraints of an optical

Table 2-2. Typical design parameters considered in a lasercom design control table.

Link Budget	Parameters
Received signal power	Operating wavelength Link distance Transmit power Transmit aperture area Transmit optics efficiency Transmit Strehl ratio Transmit pointing loss Polarization mismatch loss Receiver aperture area Receive optics efficiency Receiver detector field of view Receiver pointing loss Atmospheric attenuation loss Scintillation-induced loss
Received background power	Receive aperture area Receive optics efficiency Detector field of view Receive optical bandwidth Background spectral irradiance Receive optics scattering behavior Detector dark count
Receiver sensitivity	Detector quantum efficiency Detector noise characteristics • Dark count rate or • Detector Excess and thermal noise Modulation format Coding scheme

link may impose additional link outages. The design of an operational lasercom system, therefore, must address these short-term and long-term outages.

2.2.5.1 Short-Term Data Outages. The optical communications link is susceptible to a number of factors that can contribute short term signal outages, including:

1) Pointing-induced fades: Because of the narrow downlink beamwidth, dynamic pointing error on the downlink can lead to occasional signal fades. The principal sources of this pointing dynamic are the uncompensated platform vibration and the sensor noise that are coupled into the downlink line of sight. During periods of high spacecraft dynamics the uncompensated spacecraft attitude error can also contribute to the pointing-induced signal fade. Depending on the bandwidth of the pointing control subsystem, pointing dynamics-induced fades have a characteristic time constant on the order of several milliseconds to several seconds.

2) Scintillation-induced fades: Atmospheric scintillation can cause variation of received signal power and apparent angle of arrival at time scales on the order of tens of milliseconds. Over the collecting areas typically required for a deep-space optical link, one expects that the effect of downlink scintillation be limited due to aperture averaging effect. On the other hand, the effect of uplink scintillation fades can be quite significant. Even with multiple uplink beams, uplink scintillation fade in excess of 3–6 dB can occasional be observed.
3) Intermittent weather: Intermittent cloud coverage will cause occasional outages of the optical link. For a subsystem design that relies on an uplink laser beacon for pointing the downlink, the occasional cloud outage, if sufficiently long (tens of seconds), can cause the downlink to wander off the desired pointing location. In this case the link availability must account for both uplink and downlink outages. Intermittent weather outages can last from several tens of seconds to days, depending on the site and seasons.
4) Safety-related outages: Safety related outage during aircraft and spacecraft fly-bys can cause uplink outages on the order of several to tens of minutes. If the outage periods exceed the capability of flight terminal to hold its pointing position, then the uplink outage will also translate to downlink pointing outages.

Depending on the outage durations, short-term outages may be addressed using either a data retransmission protocol and/or by interleaving the data over several independent fade periods.

2.2.5.1.1 Signal Fades and Data Interleaving. In the presence of rapid time-varying fades, one can budget a larger amount of link margin to ensure that the probability of a fade with depth exceeding the margin is negligible. Alternatively, for a coded optical link, one can interleave the transmit data such that the signal fade is spread over several code words. A de-interleaver at the receiving end re-assembles the transmit code words. Since the PPM symbols in each codeword might experience a diversity of fades, the occasional deep fades can be effectively corrected by the error-control codes.

In order for the interleaver to be effective, the length of the interleaving period must span a large number of independent fade periods. Due to the high data rate expected for the optical link, interleaving is an effective strategy only for short fades such as those due to pointing error and scintillation fades.

2.2.5.1.2 Retransmission Protocols. A second option to address the occasional signal fade is to rely on the retransmission protocol such as an automated repeat request (ARQ). ARQ schemes are widely used in data communications applications to provide reliable data transmission over an unreliable physical link. Because of the long RTLT involved, simple stop and wait or go-back N

ARQ schemes would likely result in severe bandwidth penalties. Instead, a selective repeat ARQ will most likely be employed. In the selective repeat ARQ scheme, the transmitter continuously transmits the downlink. If any downlink data unit is not acknowledged after a certain period, it is assumed lost and is retransmitted. Alternatively, it is also possible to implement the ARQ scheme in which the corresponding terminal explicitly sends a negative acknowledgement (NACK) signal for the lost frame.

ARQ protocols can be implemented either at the data-link layer or at the transport layer. In either case, a unique sequence number is needed to clearly identify the data unit. The receiving terminal must provide the capability to reorder the downlink frames if they are transmitted out of order (due to a repeat request). Furthermore, In order to implement an effective ARQ scheme, the spacecraft must provide sufficient onboard data storage to buffer the downlink transmission at least over one RTLT. This can drive the data storage requirement on the spacecraft.

2.2.5.2 Weather-Induced Outages. The issue of weather-induced outages is of particular concern for a free-space optical link. For the RF links, the principal effect of weather (other than high wind conditions) is to increase the system noise temperature and link attenuation, and the effect of inclement weather can generally be overcome by increasing the transmit power, or by operating the link at higher link margin. For an optical link, on the other hand, the attenuation due to clouds can be as high as several tens of decibels, and it is generally impractical to provide the link margin necessary to combat cloud-induced signal fade. Consequently, the optical link will generally require cloud-free line of sight (CFLOS) to operate. To achieve the near 90–95 percent availability currently achieved by the RF link will require considerations on the following.

2.2.5.2.1 Weather Availability at the Receiving Site. Selecting the site for the receiving terminal is critical. If the receiver is located above the cloud layer, such as on an high altitude balloon or an orbiting platform, it will be much less susceptible to weather related outages. On the other hand, such a system will have a much higher development and operating cost. Furthermore, as a space-based terminal is much more difficult to service and upgrade, the lifecycle cost of a spaceborne terminal will generally be much higher than the ground-based terminal. For the foreseeable future, therefore, it is likely that the Earth receiver will be located inside the atmosphere, and the location of the ground terminal needs to be carefully selected to minimize the amount of cloud covered days.

The percentage of time a given site can maintain CFLOS with the spacecraft is a function of site location and the season. Some sites also exhibit diurnal variation in cloud coverage. However, single-station weather availability will generally be less than 70 percent, even at outstanding sites such as the southwestern United States. The single-station availability can further decrease if significant re-acquisition time is required, especially for partly cloudy days.

2.2.5.2.2 Site Diversity with Multiple Ground Stations. Another method of achieving high weather availability is to use site diversity with multiple ground stations. If *N* stations, located at independent weather cells, are visible from the spacecraft, and each station has a weather availability of p, then the network availability is simply the probability that at least one station has a CFLOS to the spacecraft, and can be written as

$$\text{Network Availability} = 1-(1-p)^N \tag{2.2-9}$$

With a large number of ground stations, therefore, one can achieve the required network availability. An example global site placement is shown in Fig. 2-9. With nine sites, each with 67 percent availability, the network can provide a 96 percent availability.

2.2.5.3 Other Long-Term Outages. In addition to weather-related outages, the optical link is expected to experience other long-term outages. One such outage is the solar conjunction (opposition) outage when the Sun-Earth-probe (SEP) or Sun-probe-Earth (SPE) angles are small. At the Earth receiver, low SEP angle implies that the spacecraft is visible when the receiver boresight is close to the Sun. Since the solar radiation is several orders of magnitude stronger than the signal, communications are not possible with the Sun in the field of view for a ground-based direct-detection receiver. However, even when the Sun is not directly in the field of view, scattering due to both the optical surfaces and telescope structure can introduce elevated background levels at small SEP angles to degrade or prevent communications. Furthermore, solar radiation reflected by the telescope can concentrate on the structure and pose a safety hazard on both the facility and the personnel. For the flight terminal, the small SPE angle also implies that the spacecraft's pointing and tracking detector will experience an increase in background noise. This can lead to an increase in pointing error and, at worst case, an inability to detect the Earth image or uplink beacon signal on the focal plane. Good stray-light rejection design is essential to improve the tracking performance at low SPE angle. It should be noted that low SPE angle occurs both during solar conjunction and during opposition. As a result, missions flying optical-communication payloads will likely experience both conjunction and opposition outages; as opposed to RF systems which experience only conjunction outages.

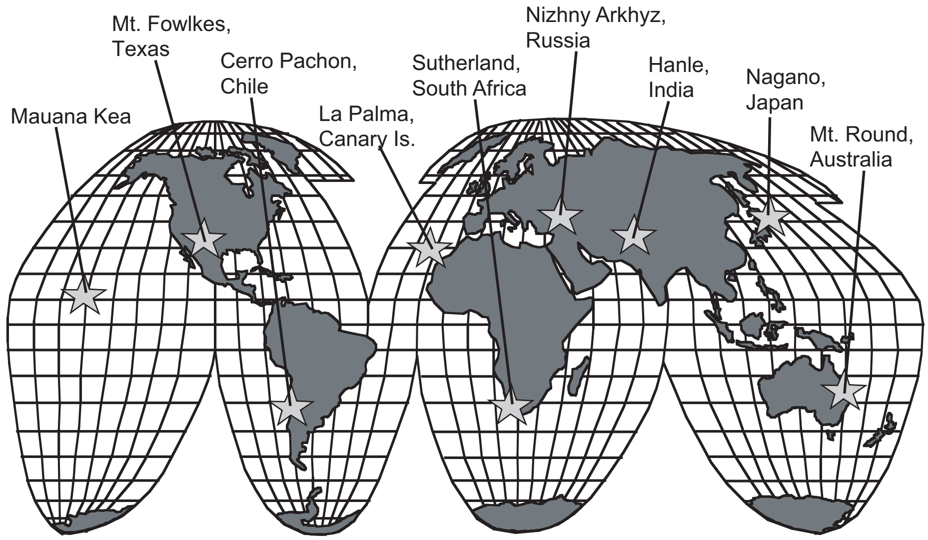

Fig. 2-9. Example multi-site optical network designed for mitigation of weather-induced outages.

In order to limit the conjunction related outages, one must take active measures to limit the amount of scattered sunlight being collected by the detector and to protect the telescope during periods of near-Sun operations. This can be accomplished by (a) employing a solar window to reduce the amount of direct sunlight being collected by the telescope, (b) limiting the amount of direct sunlight on the optical surfaces with baffles and other structures, and (c) controlling the surface quality and contamination level to limit the amount of scattering, and using a combination of Lyot and field stops to limit the out-of-field background.

The solar opposition period also poses a unique challenge to optical communications payloads that rely on the solar-illuminated Earth or the Earth-Moon system for pointing reference. As viewed from the spacecraft, the Earth-Moon system will be barely visible, as only a small fraction of the Sunlit surface is visible from the spacecraft. This reduced photon flux at the receiver can severely limit the tracking frame rate when the solar background interface is most severe. Therefore, even though the Earth receiver will have a favorable background noise condition during solar opposition, the reduced pointing performance at the spacecraft will lead to an effective communications outage.

In addition to the solar conjunction period, long-term laser-communication outages can occur when the spacecraft's attitude is constrained to prevent pointing of the body-mounted flight lasercom terminal at the Earth. Such attitude-constrained periods can occur during nominal mission operations or during periods of spacecraft fault protection. Examples of nominal mission attitude-constrained periods include the inner cruise period for Cassini when the high-gain antenna (HGA) needed to be Sun-pointed for thermal reasons and the thrusting cruise phase for Deep Space 1 when the spacecraft needed to be pointed along the thrusting vector of the solar electric propulsion system. During attitude-constrained periods, the spacecraft may be prevented from pointing the optical boresight to Earth for very long periods of time. The Cassini inner cruise periods, for example, lasted from October 1997 through February 2000.

For RF systems, mission coverage during these attitude constrained mission phase and during fault protection period is generally accomplished using low gain antennas. Since it is impractical to implement an optical low gain antenna, communications over these attitude constrained mission phase will generally be limited unless the optical system is gimbaled to provide a wide range of coverage or that an auxiliary RF system is used to provide mission coverage during these periods.

2.2.5.4 Critical-Mission-Phase Coverage. A related issue to the long-term mission outage is the requirement for link availability during critical mission phases, such as during orbit insertion burn or during the entry-descend-landing (EDL) mission phase. Coverage during these critical period has been deemed critical due to lessons learned from past mission failures (e.g., Mars Observer and Mars 98 [7]). Unlike weather-related outages that can be overcome by buffering the data onboard the spacecraft, critical-mission-phase coverage will require that the communications link be available at the precise moment of each such maneuver. Given that a ground-based receiver will almost always be susceptible to weather-related outages (unless a space-based receiver is implemented), critical-mission-phase coverage should be accomplished using RF links, and missions flying a lasercom system will generally need to also provide an auxiliary RF link. Such a link may also provide the ability to communicate during any attitude-constrained mission phases, as well as during spacecraft fault protection periods when the ability to precisely point the downlink to Earth using the lasercom terminal may be compromised.

2.3 Beam Pointing and Tracking

Due to the narrow transmit beamwidth, accurate pointing acquisition and tracking are critical to the deep-space laser communications system implementation. For a typical deep-space lasercom terminal, the required pointing accuracy is a small fraction of a microradian. The flight lasercom terminal must achieve this pointing accuracy in the presence of spacecraft platform jitter and attitude-control deadband, both of which can be several orders of magnitude larger than the required pointing accuracy. Inaccurate beam pointing can result in large signal fades at the receiving site and a severely degraded system performance.

2.3.1 Downlink Beam Pointing

In order to achieve sub-microradian level pointing accuracy in the presence of spacecraft platform jitter and attitude-control deadband, a dedicated pointing control subsystem needs to be an integral part of any flight lasercom system design. Furthermore, design of the pointing control subsystem can impose stringent requirements across the optics, control, and mechanical design of the lasercom terminal. In contrast, the beam-pointing requirement for a RF communication system is much less stringent: a 1-m antenna operating at X-band requires a pointing control accuracy of 0.1–0.5 deg, and the same antenna operating at Ka-band requires a pointing accuracy of a few milliradians, both of which are well within the capability of current spacecraft attitude-control subsystems.

The problem of pointing the narrow deep-space return beam can be divided into a combination of jitter isolation/rejection, and precision beam-pointing functions. The former is the problem of isolating and rejecting the spacecraft jitter and attitude deadband in order to provide a stable transmit line of sight (LOS) in inertial space. The latter is the problem of pointing the stabilized line of sight in the direction of the Earth receiver.

2.3.1.1 Jitter Isolation and Rejection. To achieve a stable line of sight, the lasercom terminal must properly isolate and reject the spacecraft platform jitter and spacecraft attitude control errors. This is accomplished using a combination of vibration isolators and a pointing stabilization control loop as shown in Fig. 2-10.

Vibration isolation is an effective method of limiting the amount of high-frequency jitter. Figure 2-10 shows a set of vibration isolators that provides the principal mechanical linkage between the flight lasercom terminal and the host spacecraft. The platform jitter is low-pass filtered by the isolators, and the high frequency jitter components are severely attenuated. This effectively reduces the required tracking loop bandwidth, which in turn reduces the requirements on the tracking sensors and line-of-sight stabilization elements.

After vibration isolation, the residual jitter present at the lasercom terminal can be controlled with a pointing stabilization control loop, which must provide sufficient control bandwidth and dynamic range to compensate for the residual jitter. This is accomplished by measuring the jitter at the appropriate update rate and accuracy.

The update rate required for the jitter measurement is in general an order of magnitude higher than the required closed-loop bandwidth of the jitter-control loop. The latter will depend on the effectiveness of the vibration isolation. The

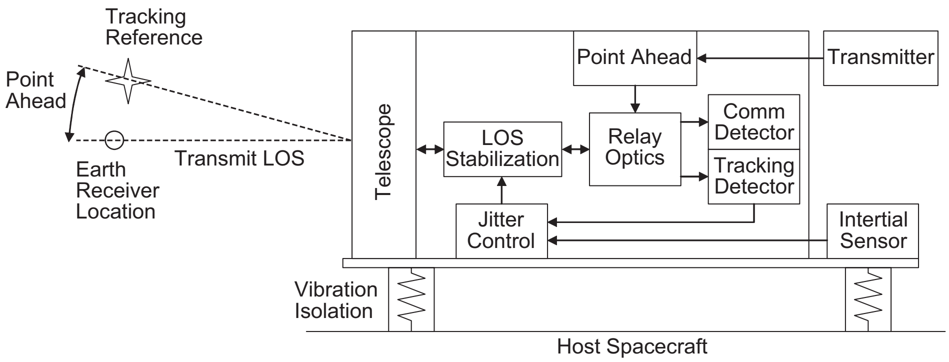

Fig. 2-10. Block diagram showing jitter isolation and rejection for a lasercom terminal.

implementation of the jitter sensor can be accomplished using a variety of means. For a near-Earth lasercom system, this is generally accomplishing by measuring the line-of-sight jitter using a beacon laser signal from the remote (ground) terminal. The narrow spectral line width of the beacon laser allows efficient background noise rejection and, because of the short range involved, the beacon signal is generally able to provide a sufficient signal-to-noise ratio to operate at the desired update rate and noise equivalent angle (NEA). For a deep-space system, on the other hand, the large link distance implies a reduced amount of beacon power available at the flight terminal. Furthermore, for a ground-based beacon, atmospheric turbulence experienced by the uplink can lead to deep and frequent signal fades that are difficult to compensate when the only reference for jitter measurement is the optical beacon.

Instead of relying only on the beacon signal from the ground terminal, the required sensing update rate and measurement accuracy can be accomplished using a hybrid pointing architecture, which utilizes a combination of inertial sensors, celestial references, and an uplink beacon. As shown in Fig. 2-10, measurements from the inertial sensors are blended with optical line-of-sight measurements derived from celestial references and/or uplink beacons to provide the jitter measurements. The inertial measurements are generally accurate at higher frequencies, but they have a lower frequency cutoff, whereas the celestial sensor and/or beacon measurements are limited by the available power to low-frequency measurements. The blending of the inertial sensor with celestial/beacon signals allows adequate jitter sensing over the frequency range of interest.

2.3.1.2 Precision Beam Pointing and Point Ahead. The net effect of the vibration-isolation and jitter-compensation control loop is to provide a stabilized line of sight referenced to the beacon (or celestial sensor) direction. The pointing and tracking subsystem must then point this LOS-stabilized downlink signal accurately at the Earth receiver. This is accomplished by accurately referencing the position of the celestial and/or beacon signals to the Earth receiver location and then applying an appropriate amount of open-loop correction (point ahead) to account for the relative velocity between the flight lasercom terminal and the Earth receiving terminal.

Pointing architecture that relies on a ground-based beacon has the advantages that the beacon is well referenced to the receiver location and is generally located within the field of view of the optical system. However, within the United States, transmission of a laser beacon signal through the atmosphere is subjected to safety coordination with the United States Federal Aviation Authority (FAA) and with the United States Air Force Laser Clearing House (LCH), and the uplink session may be punctuated to prevent illumination of aircraft and spacecraft. Since the flight terminal relies on the ground-based beacon to provide the pointing reference, the potentially nondeterministic beacon outages can lead to occasionally large pointing error and can interrupt the downlink communication session; which must be addressed via proper operational workarounds (e.g., with retransmission protocols to ensure reliable downlink data delivery).

An alternative to the ground-based beacon is to use the Earth image or celestial references to provide the desired pointing reference. This architecture has the advantage that it allows the flight terminal to point the downlink at the receiving terminal without requiring an uplink beacon. This, in turn can greatly simplify mission operations. However, practical implementation of a beaconless pointing concept is very difficult. Earth image tracking is susceptible to albedo variation, which can cause a random and time-varying shift of the Earth image centroid from its geometric center site reference. Furthermore, since the Earth images fall within the same spectral band as the solar radiation, proper filtering of the solar background can be very difficult to accomplish, especially at low Sun-spacecraft-Earth angles. Beaconless pointing using celestial reference is equally difficult to implement as it will require at least a reference source within the optical field of view. This, in turn, drives the optical design. For outer planetary missions (i.e., Jupiter and beyond), Earth will only be a few degrees from the Sun, and solar stray light can lead to an elevated background level and a higher noise equivalent angle. Although separate tracking sensors with boresight pointed away from the downlink is a possible option, practical implementation of this concept will require maintaining the precision alignment between the boresights of the lasercom terminal and the celestial tracking sensor, and can greatly complicate the mechanical design of the optical system.

In general, the location of the pointing reference is different than that of the receiving station, and the flight lasercom terminal must off-point from the pointing reference in order to position the downlink over the receiving terminal. Even if a co-located beacon is used with the receiving terminal, the relative motion between transmit and receive terminals will require that the transmit signal be off-point from the apparent beacon location so that the return signal will arrive at the receiving terminal at the proper spatial-temporal location. This pointing offset is known as the point-ahead angle. Because it is generally impractical to offset the beacon and the receiver location at precisely the point ahead angle, point-ahead function is usually accomplished open-loop. The point-ahead angle required for deep-space missions is typically on the order of several hundreds of microradians, compared to the tens of microradians for near-Earth lasercom systems. This large point ahead drives both the field of view of the optics as well as the design tolerances of the optical system as it needs to maintain its performance over the relatively large angular separation between the pointing reference (beacon) and the desired downlink direction.

2.3.2 Uplink Beam Pointing

Uplink transmission from the ground to the flight terminal is needed to provide an optical command path and to provide a pointing reference if the flight terminal relies on a beacon signal to point the downlink. In both cases the ground terminal must deliver the required irradiance at the flight terminal while minimizing the magnitude and frequency of the signal fade. The latter is due to the time-varying higher order modes in the wavefront distortion introduced by the atmospheric turbulence which, when propagated to the far field, can result in strong fluctuations of the far field irradiance.

In order to accurately point the uplink at the spacecraft, one must provide the requisite pointing reference. This pointing reference can be a nearby star or planet. Alternatively, the optical downlink itself can be used as a pointing reference, although since the uplink is also used to provide the pointing reference, one must carefully address the pointing acquisition issue. Since the atmospheric turbulence effectively broadens the transmit signal (by breaking up the wavefront into small cells with coherence diameter of approximately r0, the Fried's parameter), the required uplink pointing accuracy is generally looser than the downlink (on the order of a few microradians). Such a pointing accuracy is within the capability of a well-instrumented telescope; provided that a proper mount-calibration has been conducted using stellar references nearby to the spacecraft position.

Even though the required uplink pointing accuracy can be achieved, the presence of the uplink signal scintillation can affect both the communications and the beacon-tracking performance. For the communications link, the occasional signal fades translate to periods of high error rates, which can be controlled through coding and data interleaving. When the uplink is used to provide a pointing reference, the signal fades translate to periods of higher noise equivalent angle and can degrade the pointing control performance.

The period and duration of a signal fade is a function of the turbulence parameter r_0 the wind speed, and the uplink signal configuration (i.e., the beam divergence and number of transmitted beams). In general, fluctuations in the far-field irradiance profile introduced by turbulence can be reduced by increasing the beam divergence, and by transmitting multiple mutually incoherent beams. If these beams are spatially separated to the extent that they pass through portions of the atmosphere that are largely uncorrelated, the likelihood of all the beams simultaneously being directed off axis will be substantially reduced relative to the likelihood of the same result for a single beam. In general, increasing the number of beacon laser beams can lead to fewer scintillation fades, which in turn, can improve the spacecraft pointing control performance. A recent study by the Optical Science Company [8] indicated that 8–16 independent beams will generally lead to very infrequent fades. Figure 2-11 shows the result of a computer simulation which plots the cumulative probability versus the on-axis power at the far field. As can be seen from this study, the probability of experiencing a large signal fades decreases rapidly with increasing number of uplink beams.

In addition to the probability of fades, the frequency and duration of the fades are also significant performance drivers. The frequency and duration of fades are related to the temporal nature of the turbulence by which they are induced. When turbulence changes more rapidly, fade events occur more frequently, but with a correspondingly shorter duration. The time scale of the turbulence evolution can be characterized in terms of the Greenwood frequency, f_G,

$$f_G = 0.255\left[k^2 \sec\psi \int dh C_n^2(h) v(h)^{5/3}\right]^{3/5} \tag{2.3-1}$$

where C_n^2 is the altitude-dependent turbulence profile and $v(h)$ is the wind profile. Turbulence-induced events will generally occur on a time scale of roughly $1/f_G$. The value of the Greenwood frequency, under typical conditions, is on the order of 30 Hz. That is, the turbulence-induced events will tend to occur on a time scale of tens of milliseconds. In order to employ a ground-based beacon as a pointing reference, the flight terminal pointing-control loop must be capable of tolerating the pointing-induced signal fade. That is, it must either have sufficient power margin or a sufficiently low pointing bandwidth such that the pointing-induced fades can be averaged over a sufficiently long period.

2.3.3 Pointing Acquisition

Prior to link establishment, the flight terminal and the beacon transmit terminal must establish the line-of-sight reference to each other. Since the

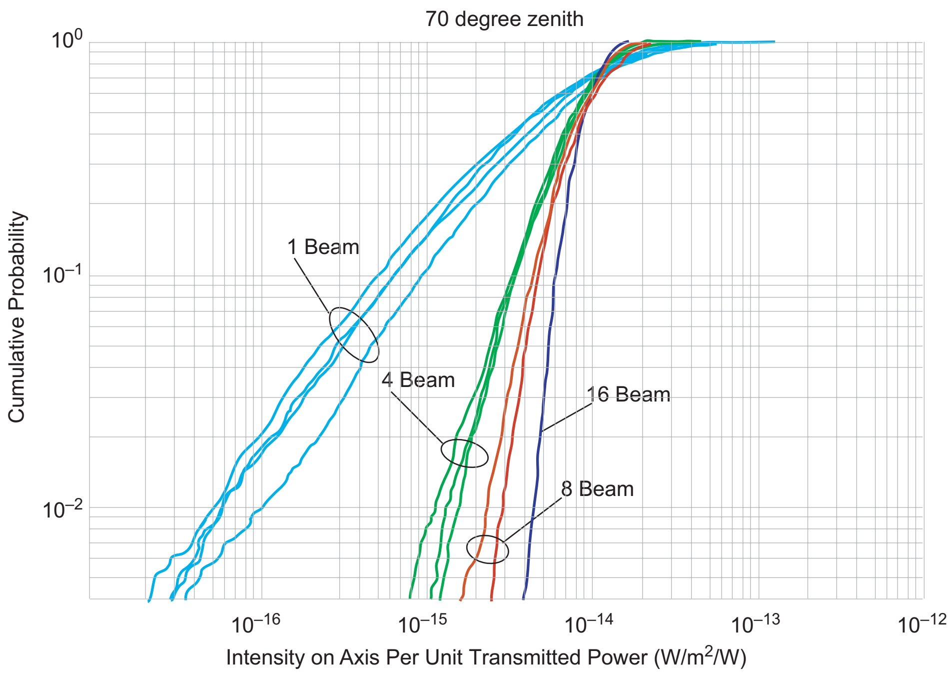

Fig. 2-11. Plot of cumulative probability versus on axis power from [7] illustrating the advantages of multiple beam uplinks.

initial pointing uncertainty can be much larger than the desired pointing accuracy, a separate pointing acquisition process is generally required to achieve this mutual line-of-sight reference. For a near-Earth lasercom system, this pointing acquisition process can be accomplished in several ways. In one concept, one terminal (the initiating terminal) slowly scans the initial uncertain region with its transmit signal. At the same time, the target terminal searches over its pointing field of view for the beacon signal. Once the beacon signal is detected, the target terminal then transmits a returns signal to the initiating terminal which, upon detecting the return link, stops its acquisition scan. Figure 2-12 illustrates this process.

The performance of this step-scan acquisition scheme depends strongly on the RTLT. At each scan step, the initiating terminal must wait at least one RTLT before proceeding. Furthermore, the drift in attitude for the transmit platform over the scan period must be smaller than or comparable to the scanning beamwidth in order to avoid missed acquisition. For deep-space missions, the long RTLT makes it impractical to employ such an acquisition scheme.

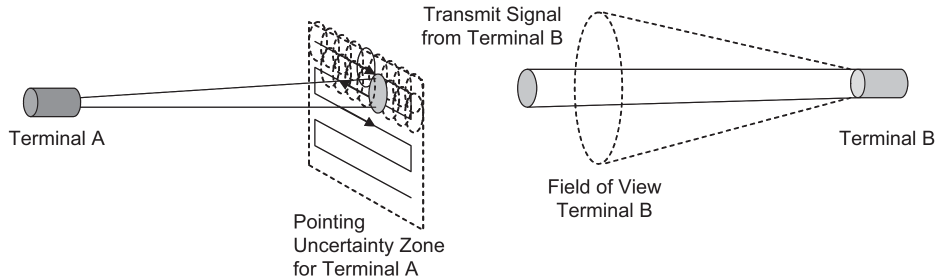

Fig. 2-12. Pointing acquisition concept in which one terminal (terminal A) slowly scans its transmit signal while at each step the other terminal (Terminal B) scans through its entire uncertain region.

Alternatively, one or both terminals can transmit a broadened beacon signal to illuminate its initial uncertainty region, while the other terminal searches for this broadened beacon signal. A variation of this scheme is for the terminals to rapidly scan the uncertainty zone with a narrow signal to provide an effectively "broadened" beacon. This "parallel" acquisition scheme is suitable if one terminal has a small initial pointing uncertainty to permit transmission of a broadened beacon while still providing adequate irradiance at the other terminal for pointing acquisition. For a deep-space lasercom system employing a ground transmit beacon, it is possible to transmit a high power signal with a suitably broadened beam to allow for adequate pointing acquisition at the flight terminal. Such a pointing scheme, however, may drive the beacon power as well as initial pointing uncertainty of the ground transmit terminal.

2.4 Other Design Drivers and Considerations

In addition to considerations on pointing and data links, a number of additional considerations may also affect the design of the flight lasercom terminal.

2.4.1 System Mass and Power

Because of the high launch cost associated with deep-space missions, flight system mass and power are generally considered to be premiums. As a result, deep-space telecom links are generally highly asymmetric: with a smaller aperture and limited transmit power on the flight terminal, and a larger aperture and higher transmit power on the ground. This approach minimizes the flight system mass and power consumption while maintaining the overall link performance. The asymmetric design is also more cost effective since it is easier to develop the large aperture and higher power transmitter on the ground. Furthermore, it is possible to amortize the cost of a larger aperture ground station over several missions. However, since the aperture and transmit laser power account for only a fraction of the overall flight terminal mass and power, continuing reduction of the flight system aperture may not significantly reduce the overall mass and power consumption. Furthermore, even though the allowable pointing error increases with smaller aperture, a smaller aperture collects a reduced amount of received tracking signal, and hence, can have a higher sensor noise equivalent angle on the tracking detector. When designing a deep-space lasercom link, therefore, care must be taken to evaluate the potential design with respect to the impact on the overall system mass and power consumption.

2.4.2 Impact on Spacecraft Design

The tight pointing requirements may affect the design of the spacecraft bus and impose constraints on mission operations. In addition to the known mass and power constraints, special care will be required to design the spacecraft in order to accommodate the flight lasercom terminal. Some of the considerations include:

1) Platform Jitter Environment: The tight pointing requirement will lead to requirements on the spacecraft vibration environment, which in turn can impose constraints on the mass balancing and structural stiffness of the spacecraft.
2) Configuration: Providing a clear optical line of sight of the lasercom terminal may impose constraints on the spacecraft configuration. This is particularly true for a body-mounted lasercom terminal, which must be pointed toward Earth within the field of view of the optical system. If an RF link is also present, the line of sight of the optical system will also need to be co-aligned with the high gain antenna boresight in order to support simultaneous RF–optical downlinks. Additionally, temperature control requirements of the lasercom terminal may impose field-of-view requirement on the thermal radiator.
3) Attitude-Control Accuracy: The attitude-control performance of the spacecraft must be sufficiently tight such that the sum of attitude uncertainty, control deadband, and point-ahead angle, are smaller than the field of regard of the lasercom pointing-control subsystem. Furthermore, depending on the pointing-control loop bandwidth, there may be constraints placed on the maximum allowable attitude rate of the spacecraft over which the desired pointing accuracy can be achieved.
4) Data Storage and Management: For reliable operation over the optical link using an ARQ protocol, the amount of data storage onboard must be greater than the expected downlink data volume over the RTLT plus ground data processing time. For a flight lasercom terminal operating at tens of megabits per second, such a data storage requirement can be a significant design driver.

2.4.3 Laser Safety

Consideration of laser safety can also be a design driver for the optical ground station. In general, laser safety considerations are limited to those for the uplink since the downlink signal, after propagating through the deep-space distance, is generally much weaker.

Personnel safety is the first priority, and an operational facility needs to comply with known safety guidelines. In addition to safety protection for the operating personnel, the system design and operation must also address the issue of aircraft and spacecraft avoidance. Emission of all Class 4 lasers above the horizon requires coordination with the United States Air Force Space Command Laser Clearing House (LCH) and with the regional FAA office for laser radiation above the maximum permissible exposure (MPE) outside restricted airspace. The regional FAA office is responsible for evaluating and determining the effect of outdoor laser operations on users of the navigable airspace (NAS). Regional offices conduct an aeronautical review of all laser operations to be performed in the NAS to ensure that these types of operations will not have a detrimental effect on aircraft operations. Requests for laser operations are evaluated by the regional offices having jurisdiction over the airspace and coordinated, if necessary, with the affected facility.

The LCH acts as the focal point to authorize laser emissions into space which may result in interference or damage to United States or foreign satellite payloads. The LCH maintains the laser facility data base, receives laser facility emission requests, determines waiver status, sends approval/denial/restrictions to the laser facilities, and processes accidental illumination information. After receiving data on the conditions of uplink emission, LCH either grants a blanket waiver for the laser or coordinates to determine safe laser firing times. The Predictive Avoidance (PA) safe firing windows provide the laser facility with safe laser start/stop times ensuring no satellite payloads will be unintentionally illuminated. LCH monitors changes in space activity and may update issued PA windows.

Due to the long safety range for high-power laser operations, the design and operations of any ground-based laser beacon must carefully consider the issue of laser safety, which may impact site selection and operational strategy for the optical link (for example, can the system tolerate occasional safety shut down). Refer to Section 6.1 for more detailed discussions on laser safety.

2.5 Summary

Because of the long distances involved, deep-space lasercom link implementation is significantly more difficult than its near-Earth counterpart. In order to deliver performance comparable or better than current state-of-the-art RF systems, the deep-space optical link will need to achieve a performance (measured in data rate-distance squared product) that is 50 dB or better than the performance achieved by the current state-of-the-art near-Earth system (i.e., 10 Gbps from GEO). This drives the transmit power and aperture sizing; the receiver's photon detection efficiency, modulation and coding; and the background rejection capability. Communications link performance considerations also lead to the use of data-interleaving and retransmission protocols to mitigate the effects of short-term outages introduced by scintillation and pointing-induced fades. Finally, considerations on the link availability also lead to ground system designs with multiple site diversity to mitigate weather-related outages.

The large link distance also drives the design of the beam pointing and acquisition. The pointing architecture used for near-Earth lasercom systems cannot be easily extended to deep-space distances due to the large propagation loss and long RTLT. Deep-space lasercom pointing will in general rely on a hybrid architecture involving the use of vibration isolators, inertial sensors, and pointing beacons.

The fact that the communications link performance and pointing acquisition and tracking considerations drive the overall lasercom system design is illustrated in Table 2-3, which shows the key performance parameters for the major flight and ground subsystems that are affected by these design drivers. Furthermore, because of the large number of common parameters, the design of the communications link is tightly coupled to that of the pointing architecture. As a result, a practical design of the lasercom system must consider performance of both the communications link and the pointing acquisition and tracking.

Table 2-3. Design considerations for the key subsystems and assemblies.

	Communications Link Performance	Pointing Acquisition & Tracking
Flight transmitter	Downlink wavelength Achievable peak and average power Modulation extinction ratio	
Flight optomechanics	Aperture size and obscuration Optics efficiency Receive optics bandwidth Transmit-receive isolation Stray light characteristics (surface quality + cleanliness) Optomechanical structural stability Transmit optics, Strehl Pointing bias and jitter	Aperture size and obscuration Optics efficiency Receive optics/solar rejection bandwidth Transmit/beacon receiver Isolation Stray light characteristics (surface quality + cleanliness) Optomechanical structural stability Vibration isolation bandwidth Optics field of view/field of regard, LOS stabilization mechanism (steering mirror) Precision point-ahead mechanism
Flight electronics	Modulator and encoder Data interleaver Downlink protocols Uplink data demodulator + decoder	Pointing control loop bandwidth and residual error Inertial sensor bandwidth and accuracy Celestial reference/beacon sensor bandwidth and noise equivalent angle
Flight receiver	Detector noise characteristic Receiver field of view (FOV)	
Spacecraft interface	Platform jitter and rate Data storage Mass and power allocations Spacecraft command and data interface Applications layer protocol stack	Platform jitter and rate Operational attitude constraints Pointing ephemeris
Ground receive optics	Downlink wavelength Aperture size and obscuration Optics efficiency Narrowband filter bandwidth Detector field of view Stray light control (surface quality and cleanliness) Receiver pointing bias and jitter	
Ground detector, receiver and decoder	Operating wavelength Detector noise characteristics Modulation format Coding Data de-interleaver Downlink protocols	
Ground network	Single vs. multiple aperture, Site diversity	Single vs. multiple aperture Site diversity
Ground beacon/uplink	Uplink wavelength Beacon pointing accuracy Beacon power Beam divergence Number of uplink beacons Laser safety Uplink data modulation and coding Uplink protocols	Uplink wavelength Beacon pointing accuracy Beacon power Beam divergence Number of uplink beacons Laser safety

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